Concentrating Solar Power Systems Analysis & Implications

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SunLab/NREL

Parabolic Trough & Power Tower

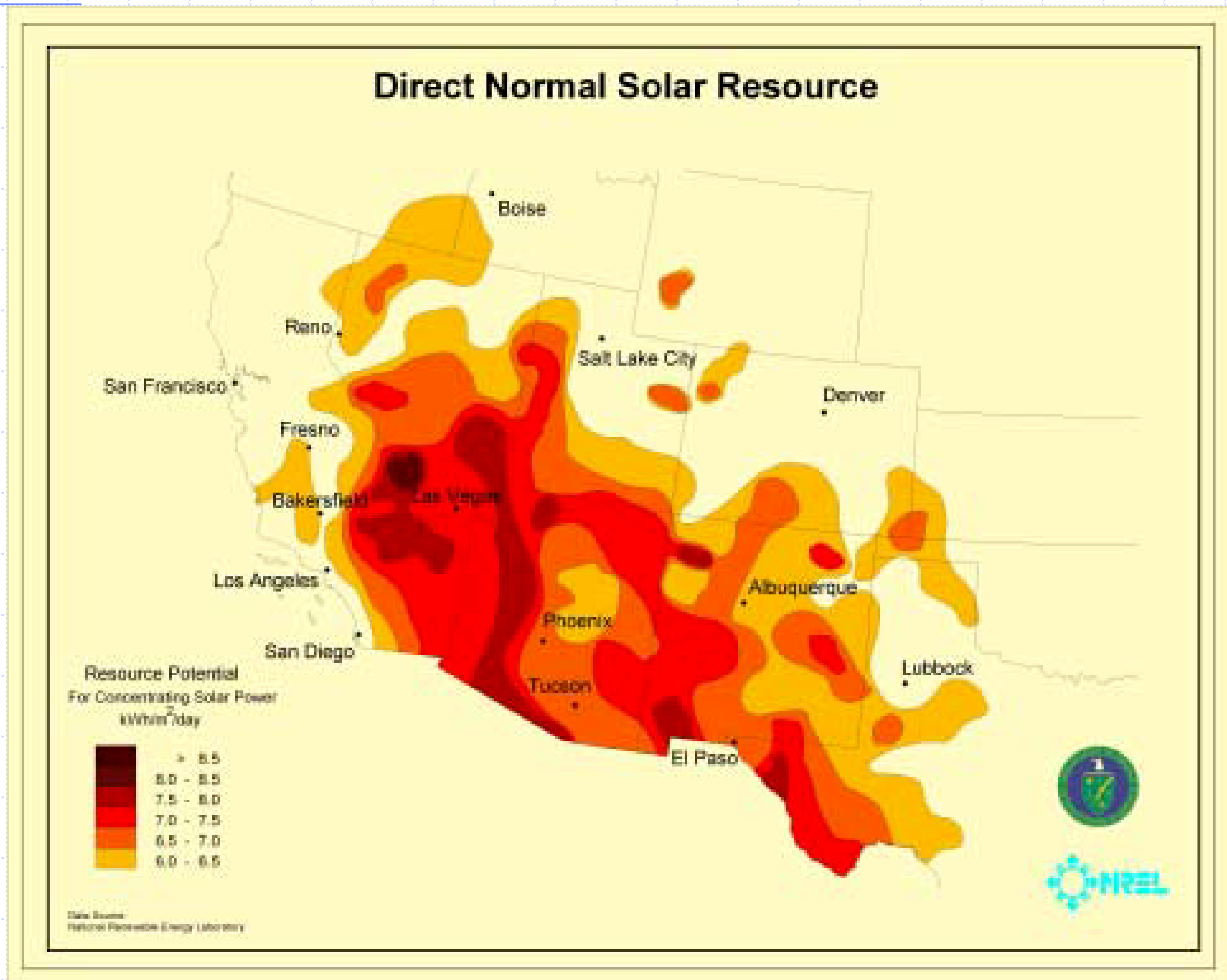
Technology Assessment

- CSP Program Status
- SunLab Technology Assessments
  - Power Towers & Parabolic Troughs
- Sargent & Lundy Review
  - due-diligence technology review
- National Academy of Science Review of S&L Report

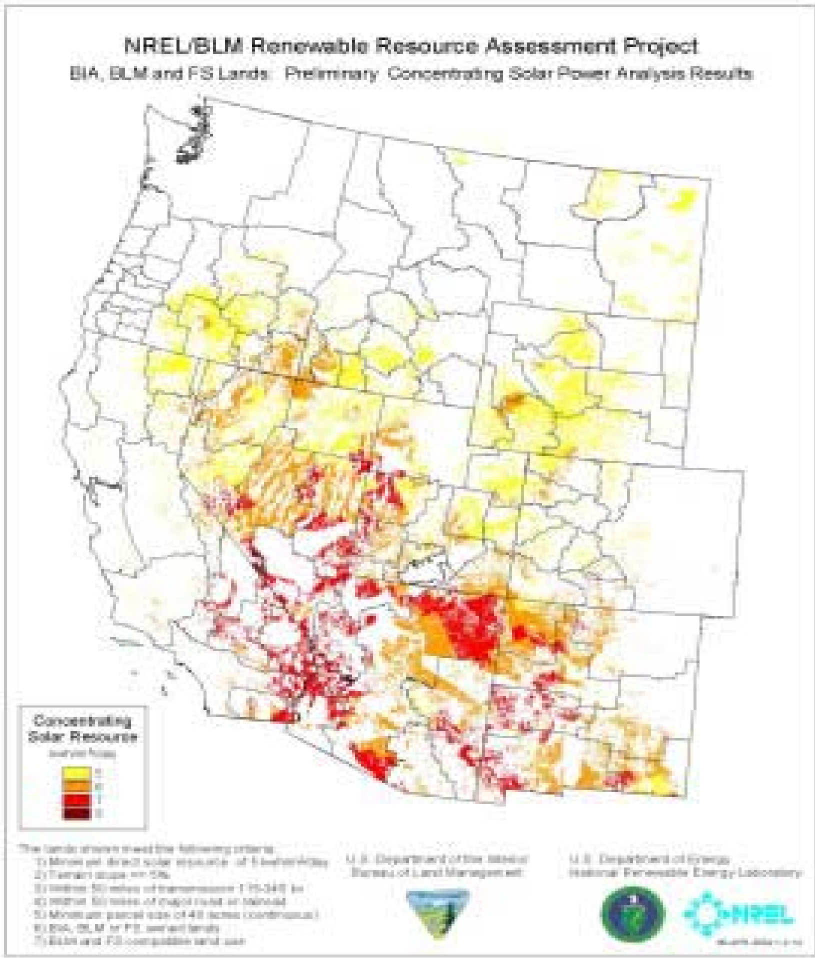
Overview
CSP Systems Approach

- Solar Resource
- Power Markets
- Parabolic Trough Case Study

U.S. DNI Solar Resource



NREL Siting Studies



Land with Slope <1%

State Resource (Area km^2)	≥6 kWh/m^2-day	≥7 kWh/m^2-day
Arizona	53,460	21,407
California	26,793	11,073
Colorado	13,327	157
Idaho	1,284	-
Kansas	9,947	-
Nevada	26,137	6,122
New Mexico	74,350	15,603
Oklahoma	6,408	-
Oregon	2,405	-
Texas	70,869	732
Utah	18,919	4,612
Wyoming	2,428	-
Total	**306,325**	**59,706**

1% of Land
>7kWh/m^2-day
~30 GWe

Power Markets

for CSP

- Market Characteristics
  - Focus on US Southwest
  - Large-scale centralized generation
  - Wholesale power market
- Competition
  - Fossil Fuel Costs
  - Electricity Cost Projections
- Value of Solar Power
  - Ability to dispatch to meet peak load

SW Natural Gas Forecast

Platts Research and Consulting

- Strong demand growth for NG in electric power sector

Near-term

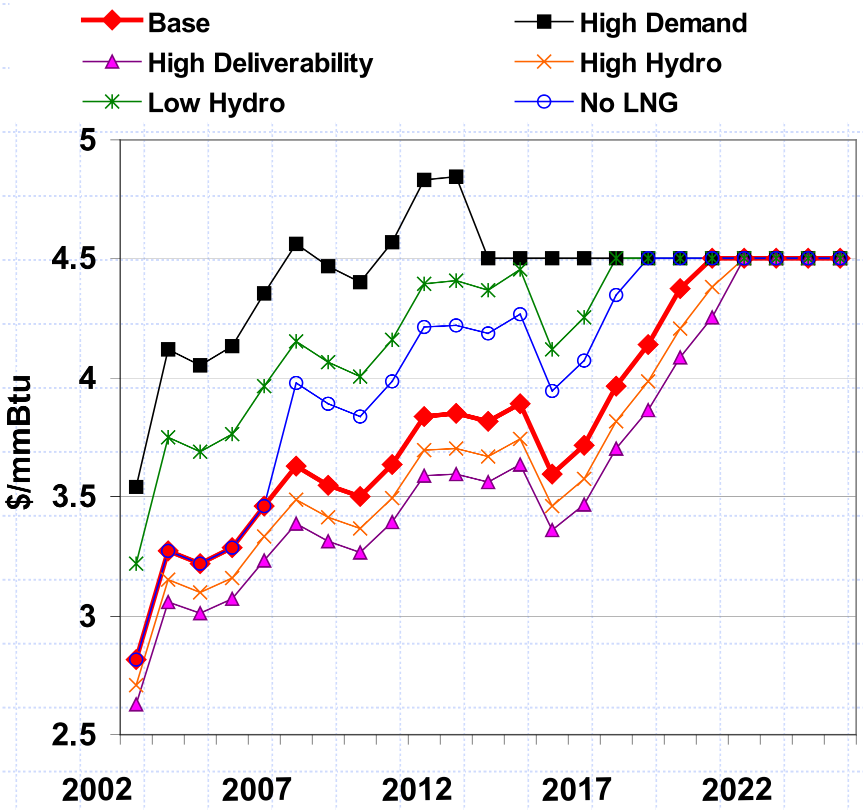
- Low 2002 prices resulted in drilling cut backs

Mid-term

- Higher exploration and production costs

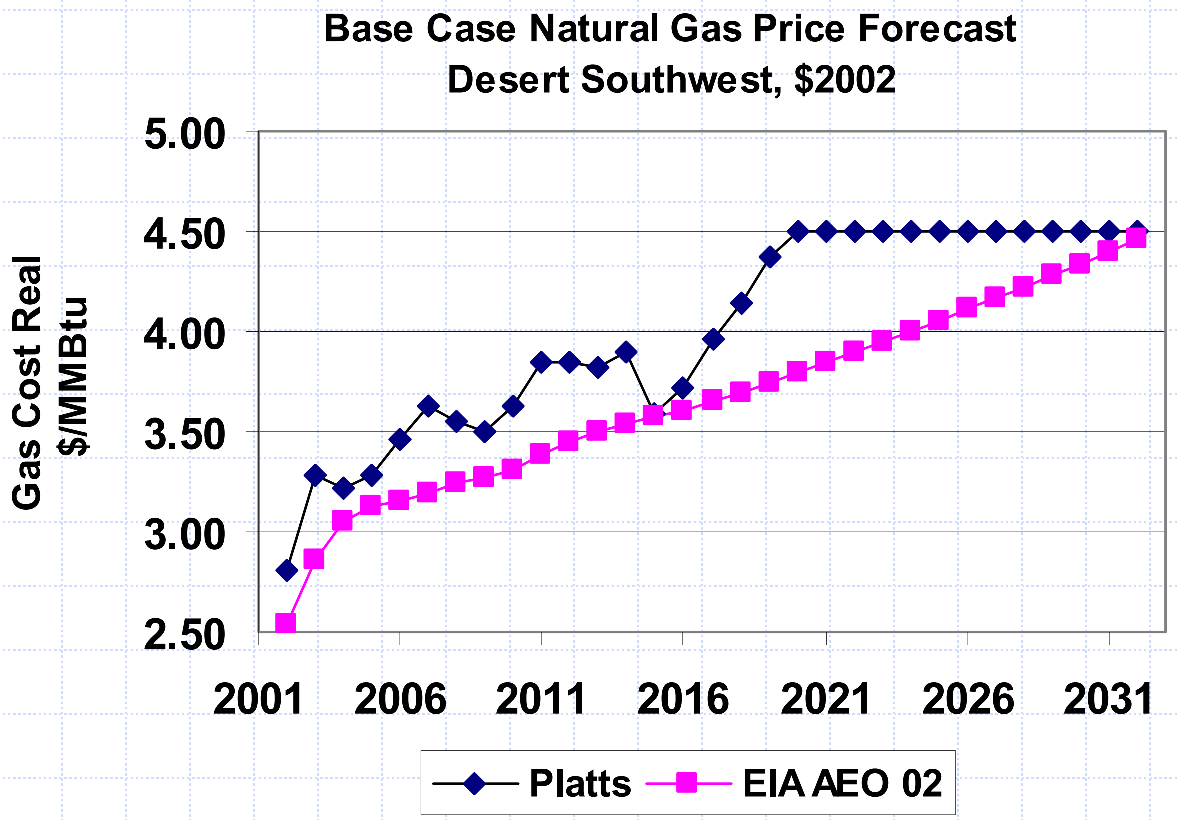
Long-term

- LNG Caps NG prices



Gas Price Forecast Comparison

Platts vs. EIA AEO 2002

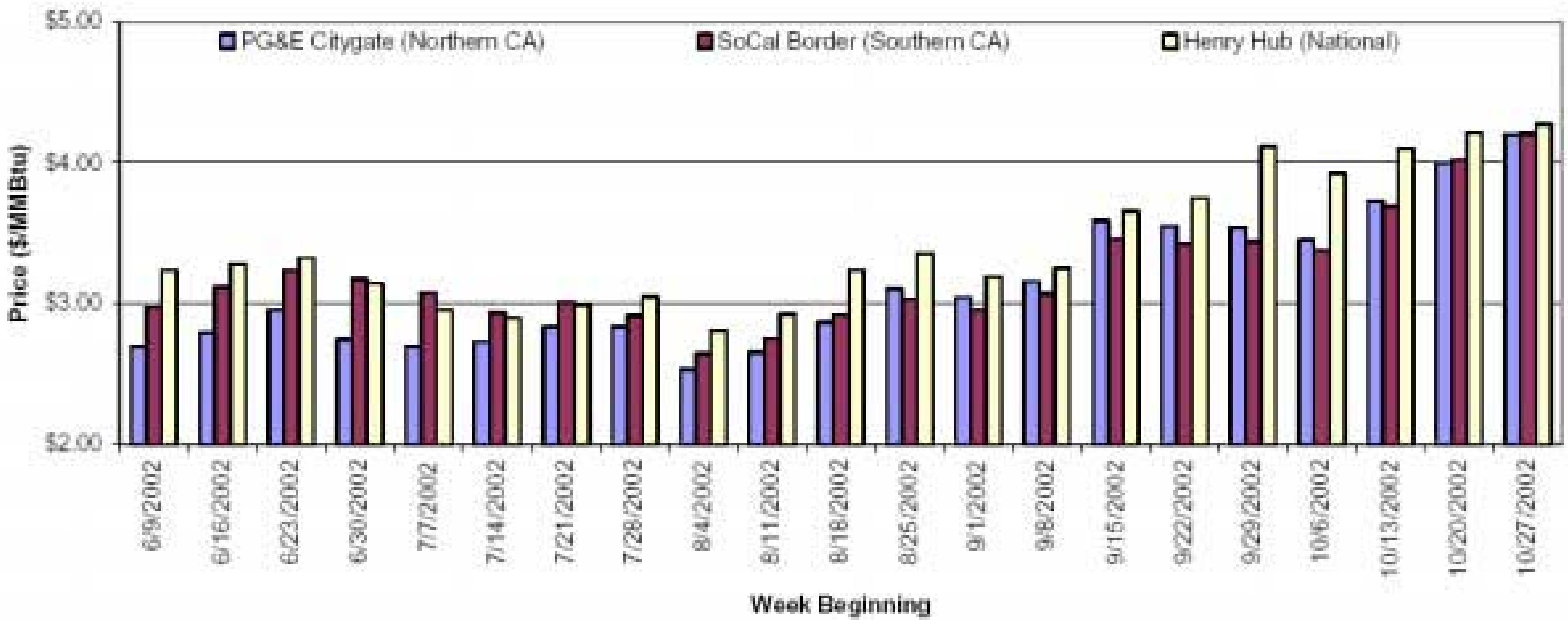


California ISO

California Independent System Operator

Weekly Average Gas Prices
June through October 2002

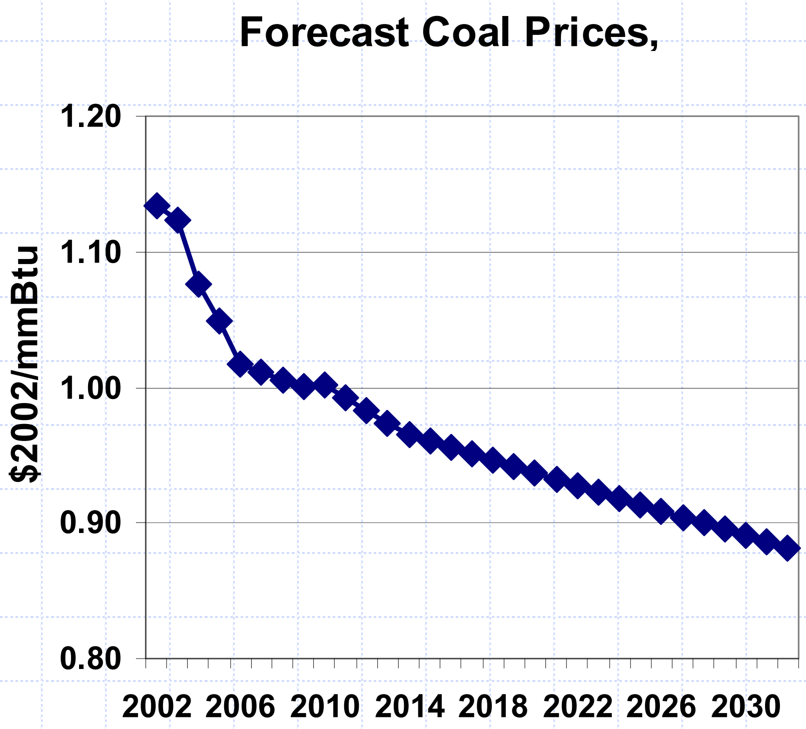
Henry Hub prices have been high due to hurricanes



SW Coal Costs

Platts Research and Consulting

- Air Quality constraints limit development of new coal power plants
- No Growth in Coal Demand
- Coal prices are reduced through mining productivity enhancements



Conventional Technology

Cost of Electricity (New Plants)

	Service	*Lowest Cost When Used*	*Corresponding Cost $/MWh*
Pulverized Coal	Baseload	60-100%	$41 to $28
Combined Cycle	Intermediate	20-60%	$75 to $41
Combustion Turbine	Peaking	0-20%	$75*

*At a 20% capacity factor.

Source: Platts Research & Consulting

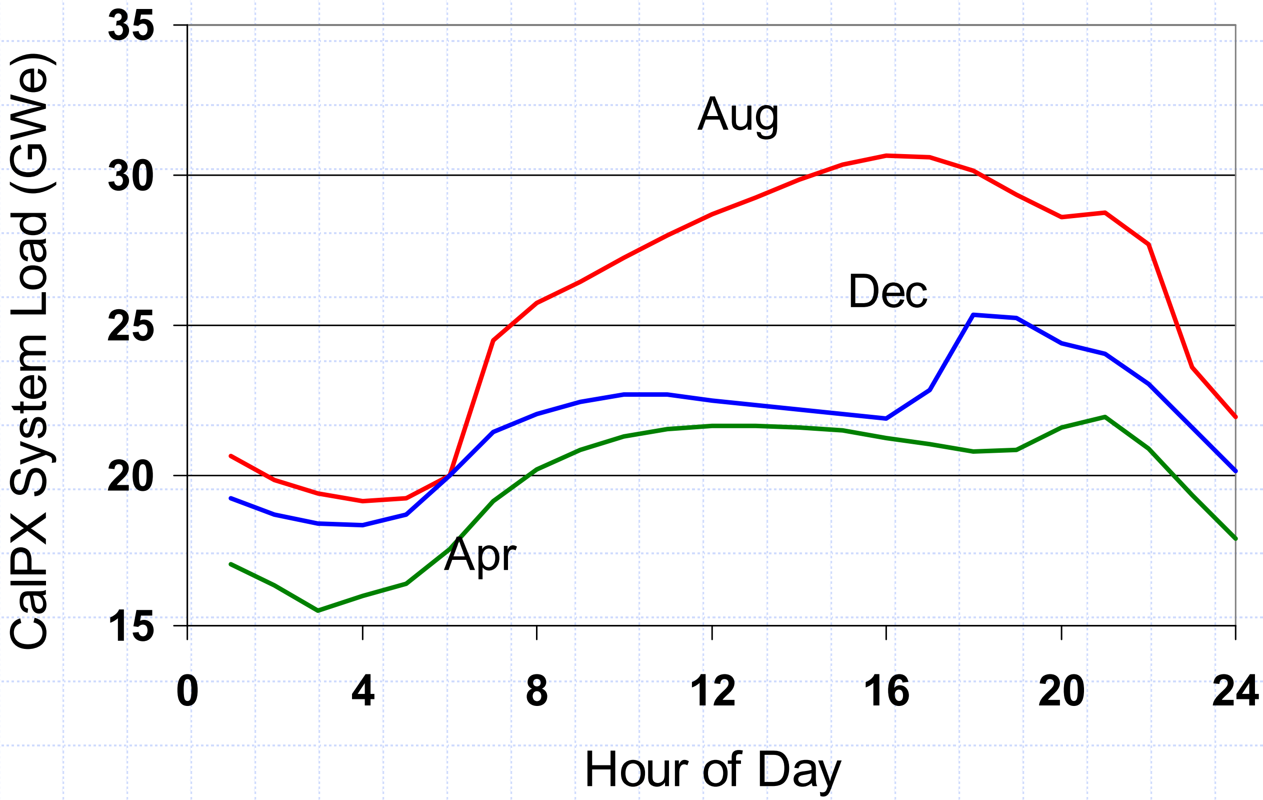
Conventional Technology

Cost of Electricity (New Plants)

	Capacity Factor	*Low Fuel Price $/MWh*	*Base Fuel Price $/MWh*	*High Fuel Price $/MWh*
Pulverized Coal	85%	30.7	31.2	32.0
Combined Cycle	60%	34.6	40.9	56.3
Combustion Turbine	10%	99.7	109.9	135.2

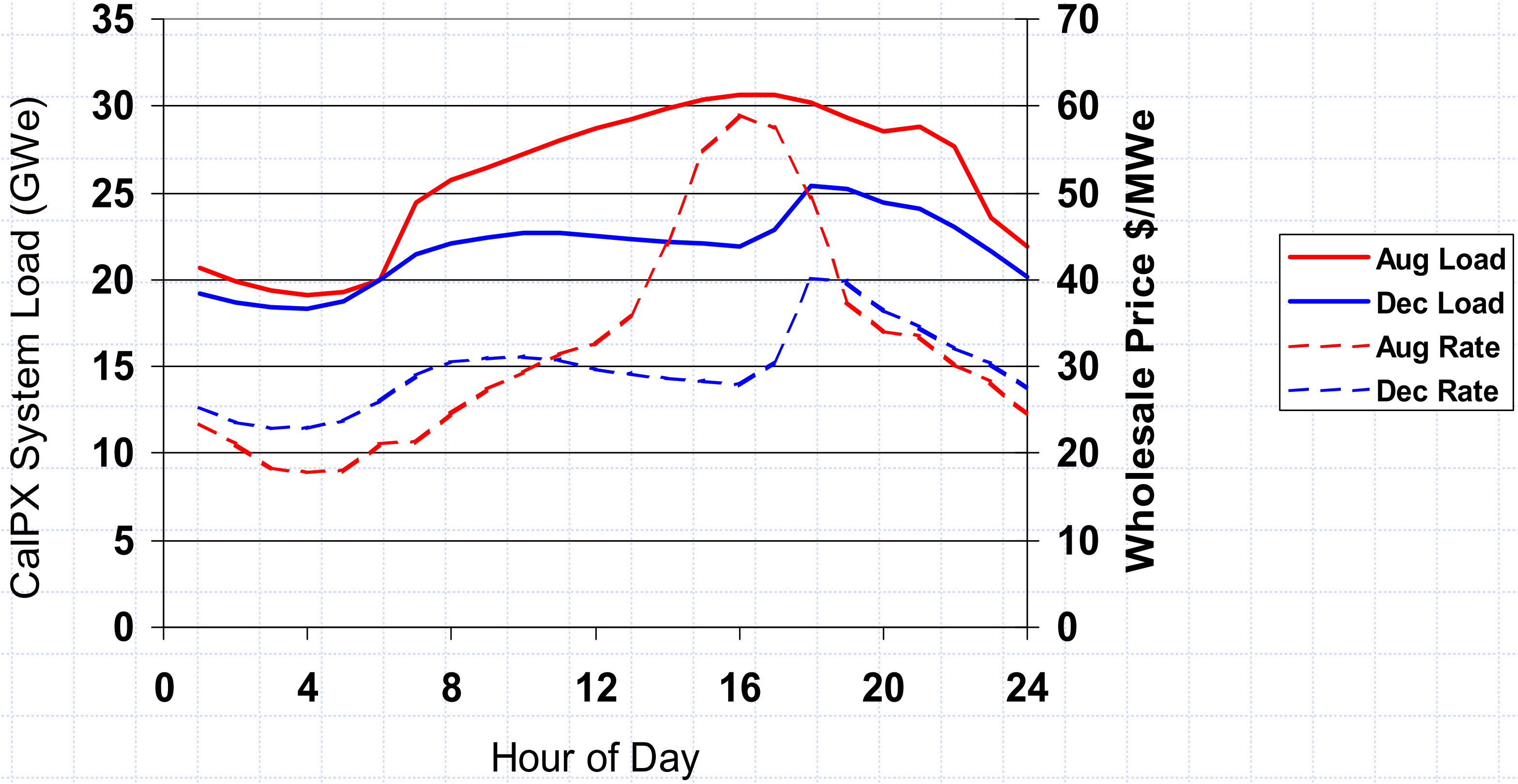
Source: Platts Research & Consulting

California System Load Profile

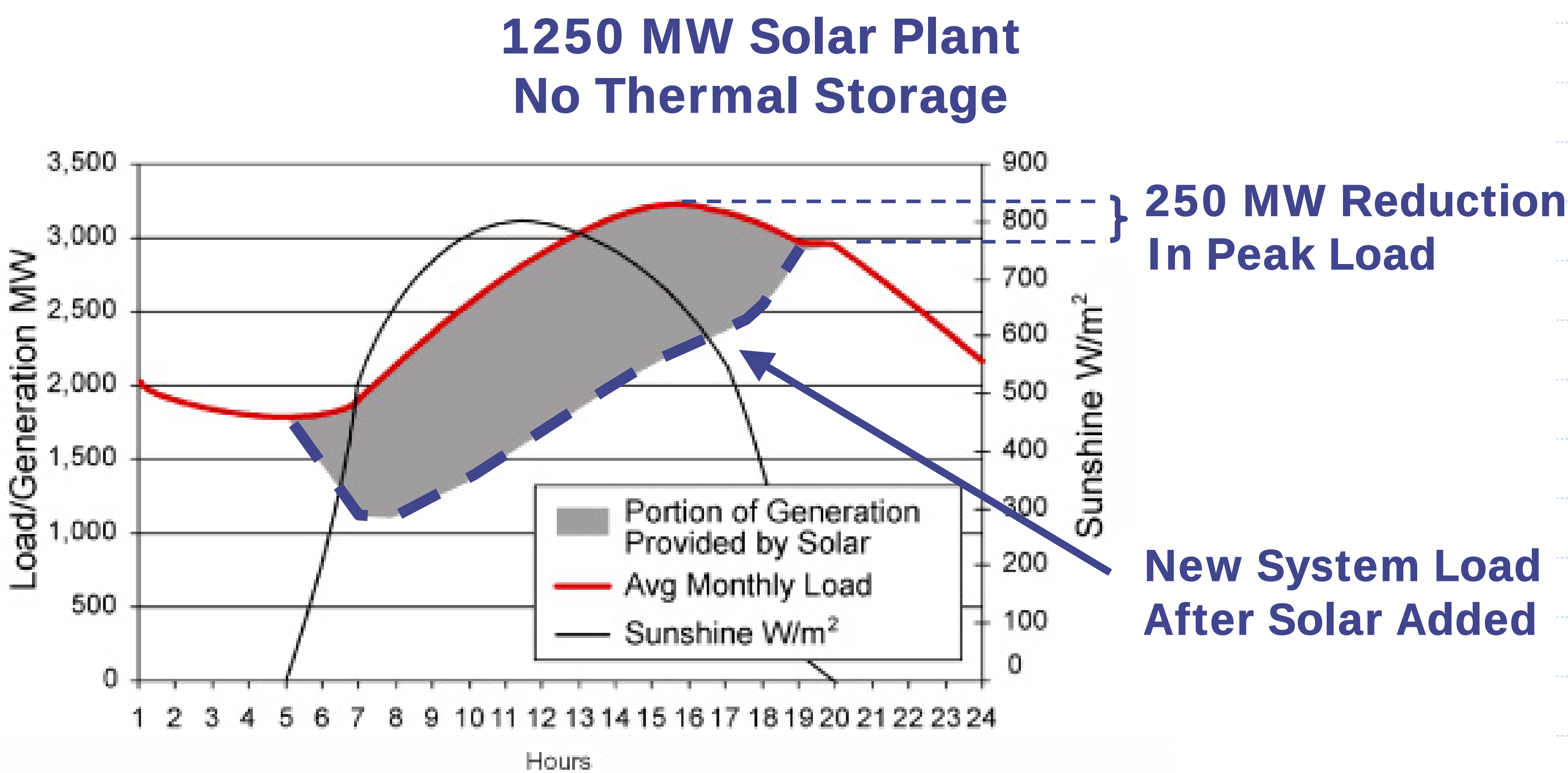


California System Load Profile

Data from 1999 CalPX



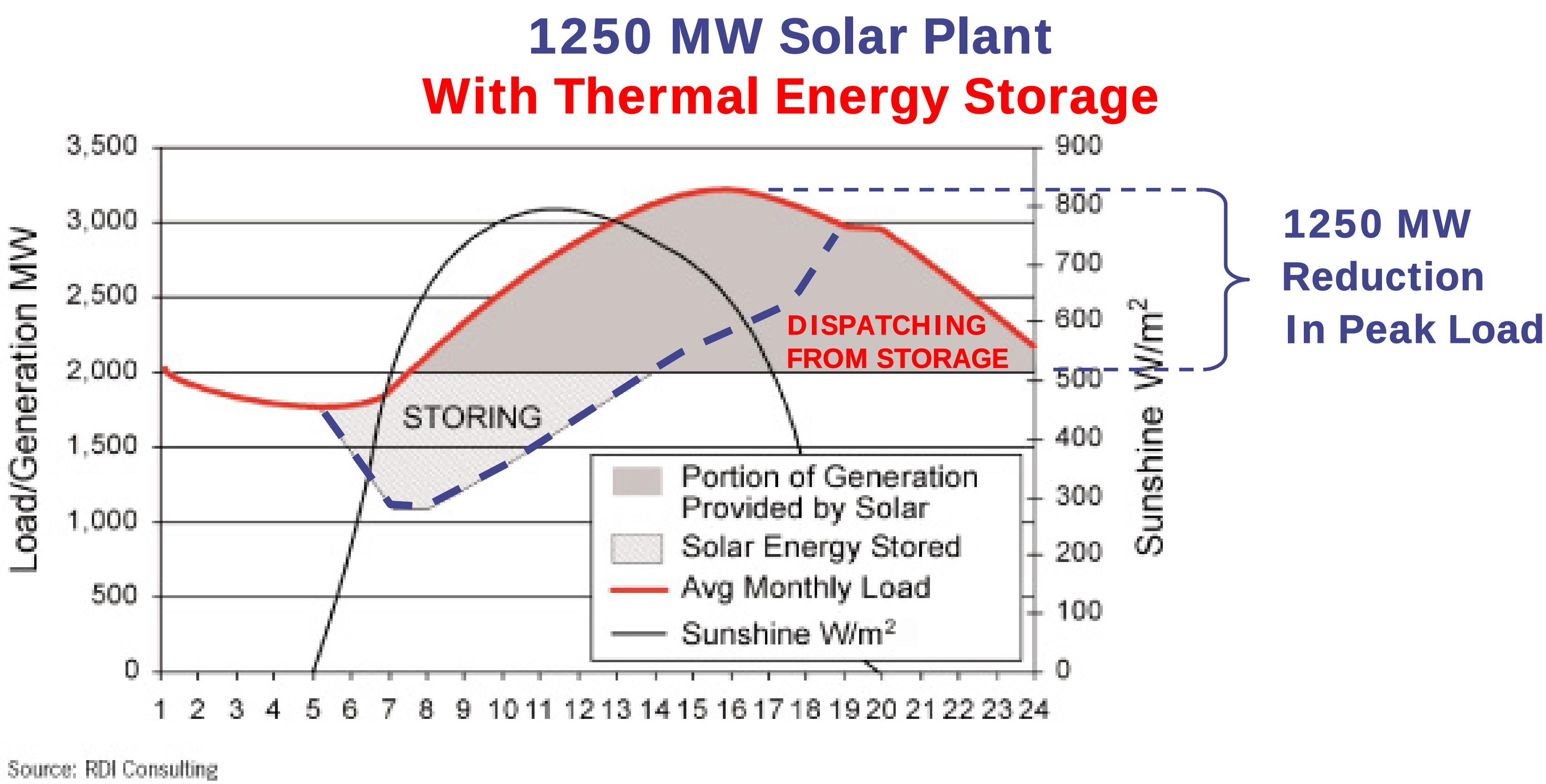
Solar Plant



Source: Platts Research and Consulting

Solar Plant

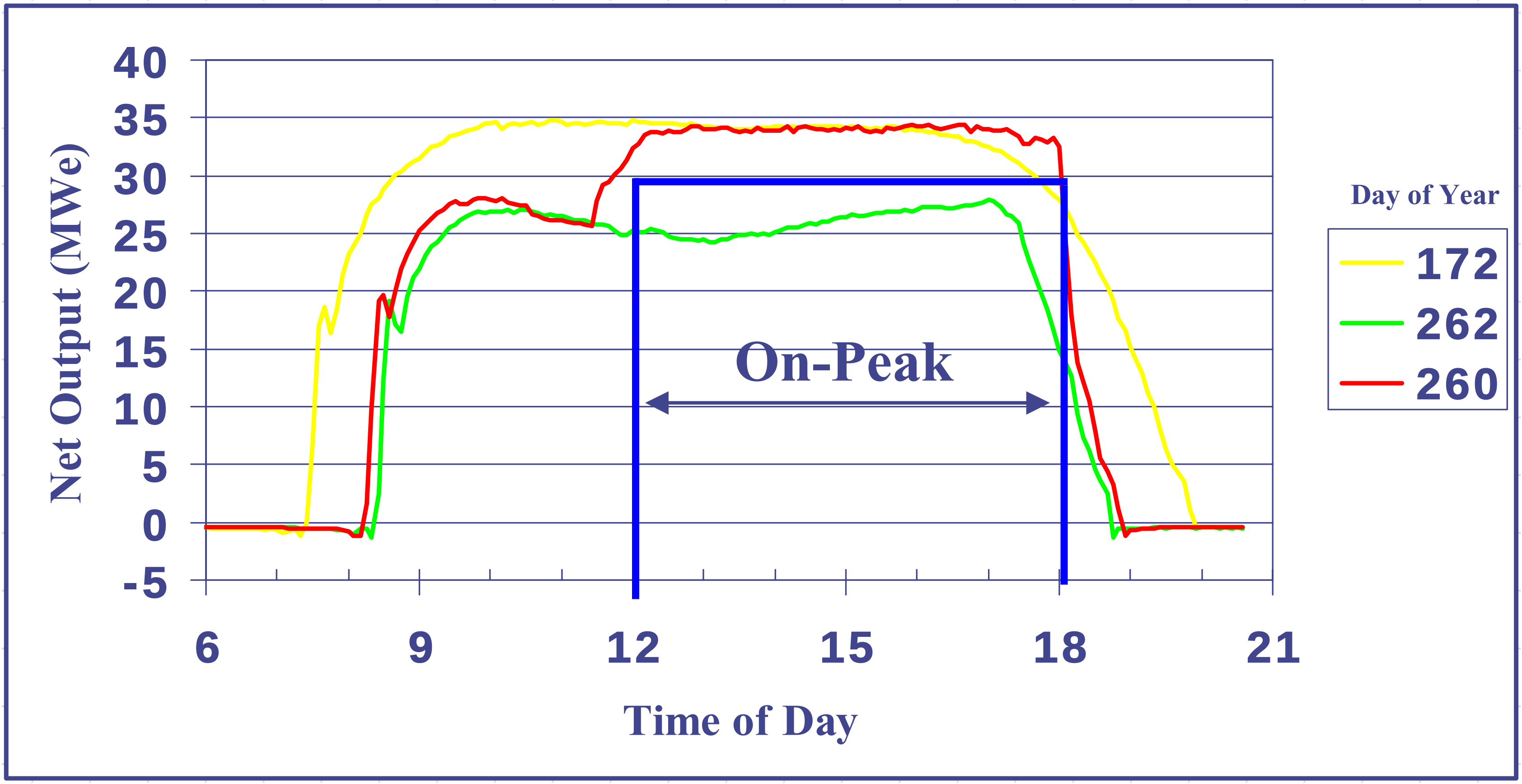
with Thermal Storage



Source: Platts Research and Consulting

Solar/Hybrid Plant

30 MW SEGS Plant Output



Wholesale Value Analysis

Case	Capacity Factor (%)	Average Price Received ($/MWh)
Average Price	100	41.17
Trough Plant No TES, SM 1.0	25.2	47.34
Trough Plant With 4 hrs TES, SM 1.5	34.1	53.40
Hybrid Trough	50.3	56.17
Wind Plant		??

Natural Gas Price $3.87/MMBtu

Source: Platts Research and Consulting

Market Conclusions

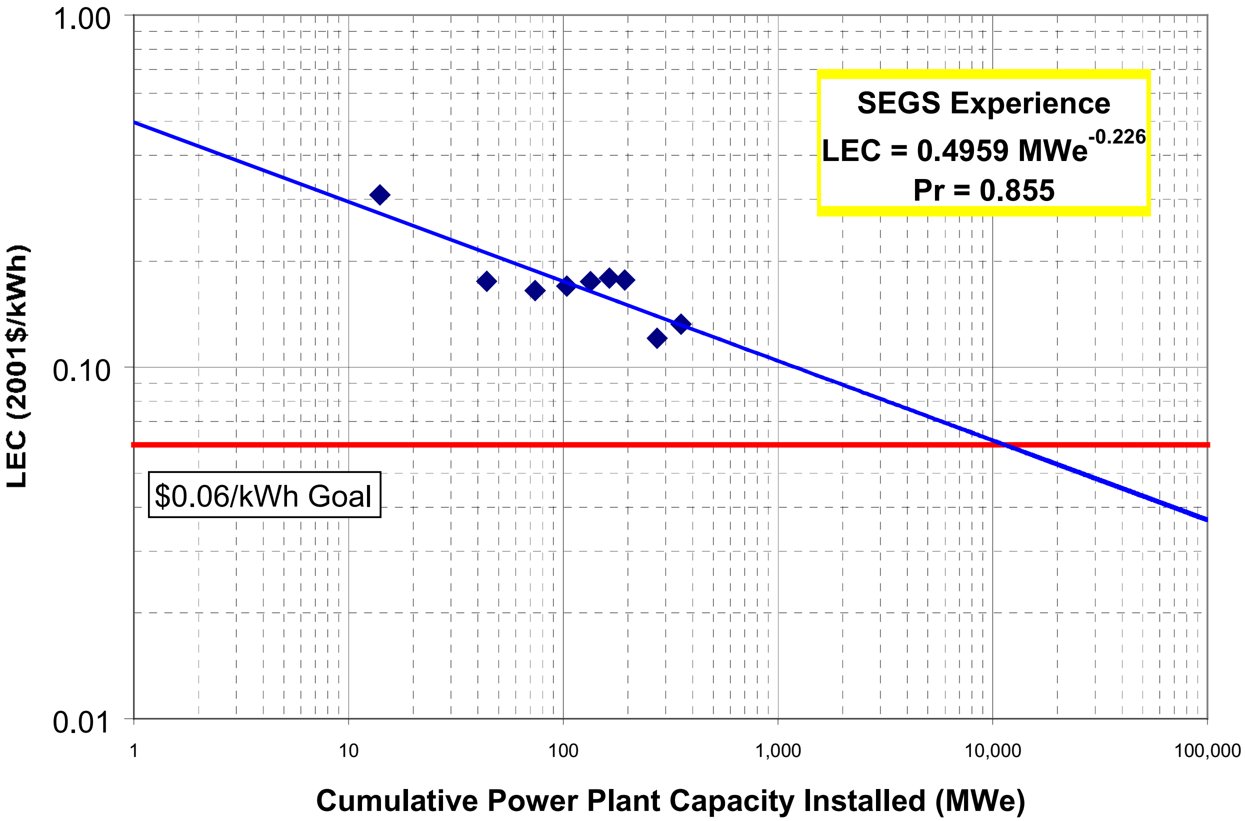
- Baseload Power – 3 to 4¢/kWh
- Intermediate Load – 3.5 to 5.5¢/kWh
- Green Adder – 0.5 to 1.0¢/kWh*

- Value of CSP 4-6¢/kWh

Trough LEC Learning Curve

How low can it go?

SEGS I-IX, 354 MWe of Trough Power Plants



Source: Luz International Limited, 1990

Parabolic Trough Case Study

What is the potential for reducing the cost of energy?

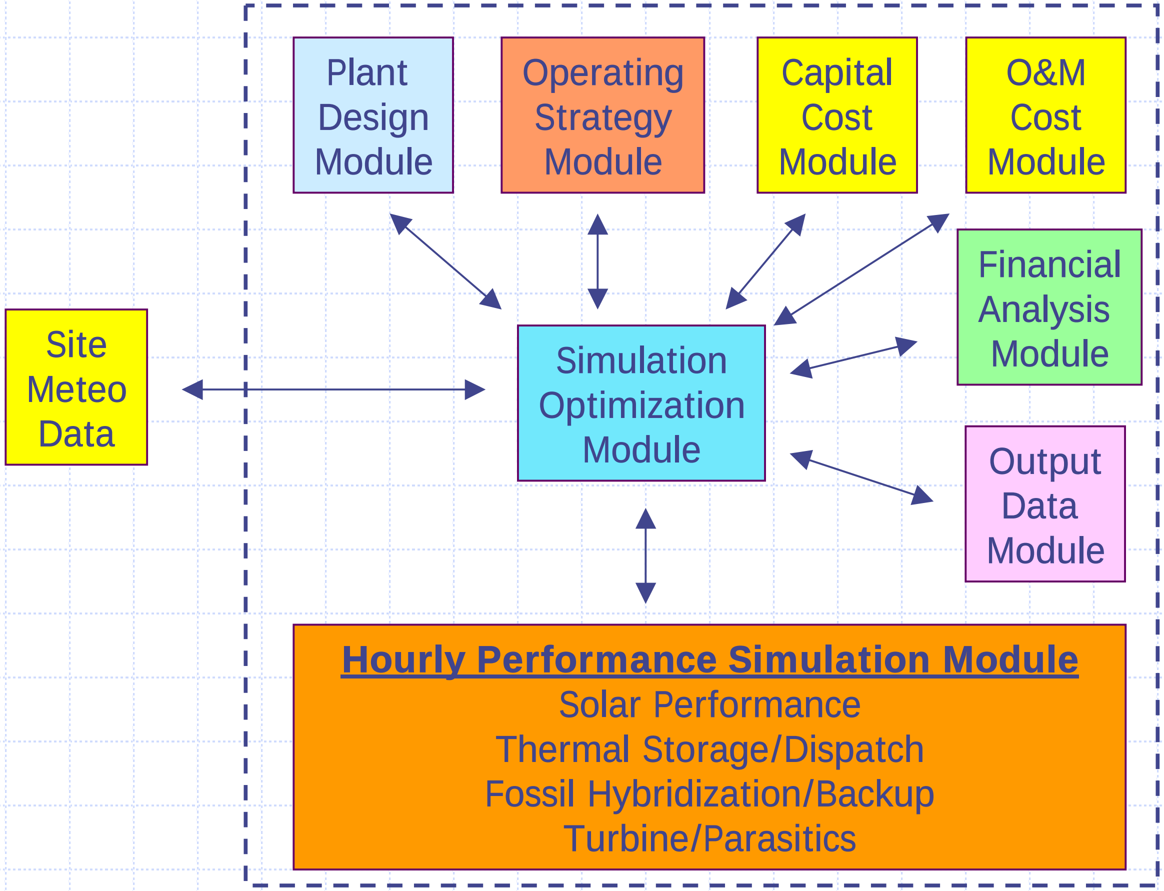
- Can Troughs Compete?
  - Market value of power 4-6¢/kWh
  - Last SEGS plant cost ~12¢/kWh
- Ways to reduce cost
  - Technology R&D
  - Policy
  - Market Deployment/Competition

Trough Technology Assessment

- Integrated performance model
- Define baseline assumptions
- Define current state-of-the-art
- Define avenues for cost reduction
- Development scenarios

Systems Analysis Approach

Integrated Trough Performance Model



Excel Spreadsheet With VBA

Trough Baseline Assumptions

- Technology
- Performance Data
- Capital Cost
- O&M Cost
- Economic Assumptions

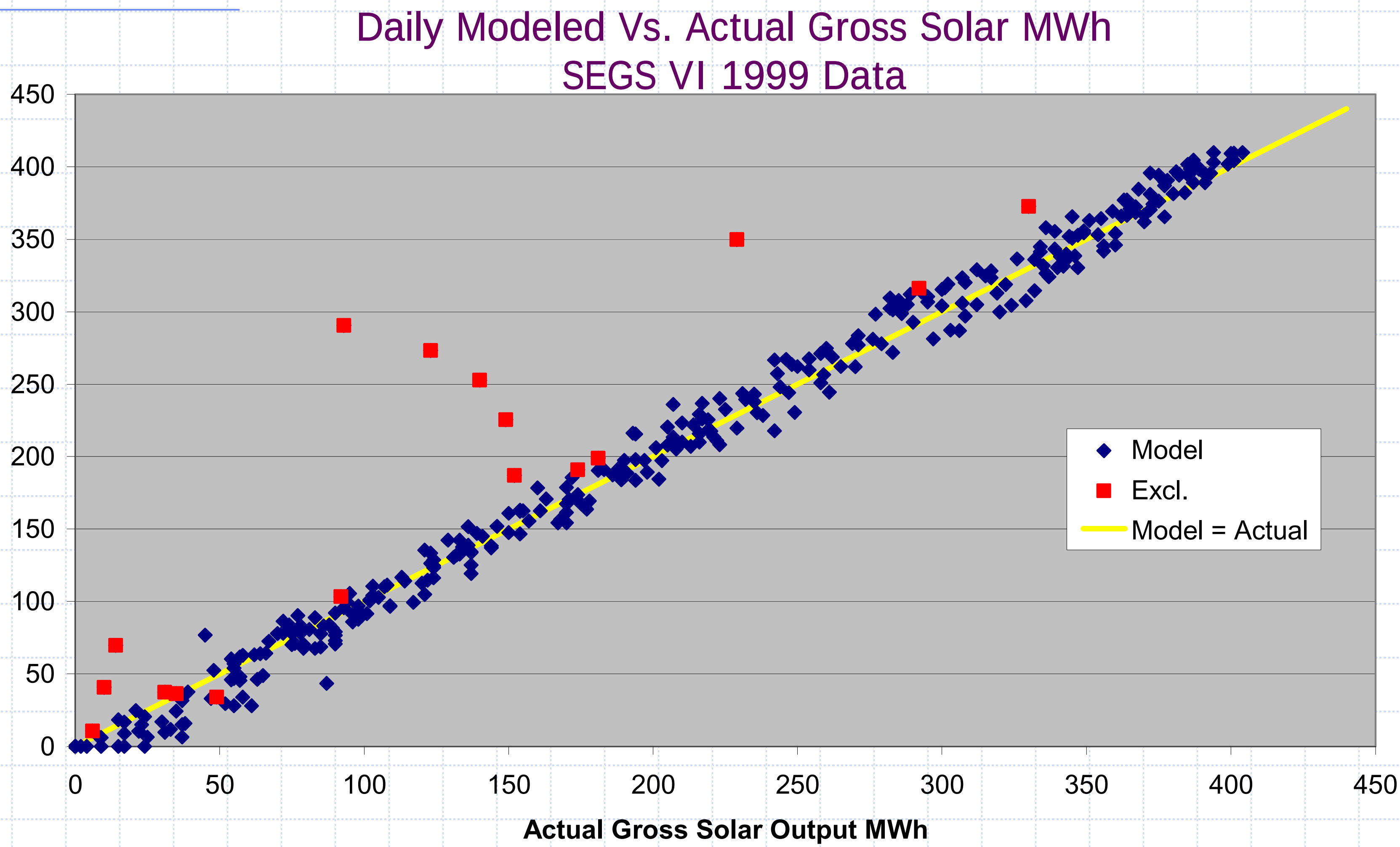
Technology Baseline

SEGS VI Trough Plant

- 30 MWe (~100 bar, 700F, 37.5% gross)
- LS-2 Collectors (391 C)
- Receiver – Luz cermet
- Hybrid (NG boiler)
- No thermal energy storage

Trough Performance Baseline

SunLab Trough Performance Model



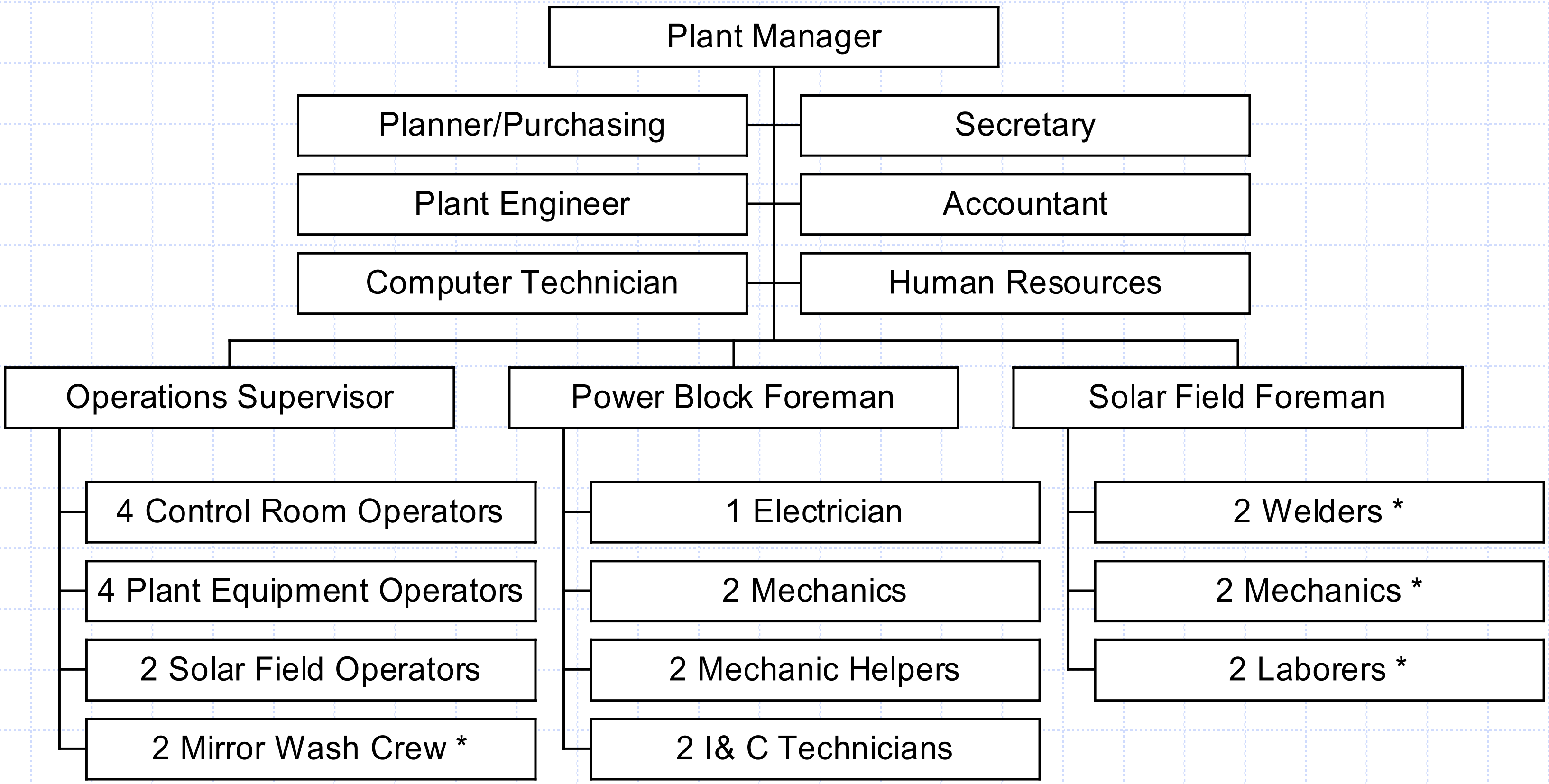
Trough Capital Cost Baseline

Cost Assumptions

- Started with Luz/Flabeg Cost Data
  - Roadmap (1998)
  - Solar Field Costs Updated from Flabeg Rpt. (1999)
- Solar Field Costs Modified for LS-2 collector
  - Structure & mirrors same as LS-3
  - Increased HCEs, drives, interconnections (ball joints)
- Thermal Storage Costs
  - Nexant Model (2000)
  - TES Development (2000-2002)

Trough O&M Cost Baseline

KJC Operating Company



* Scale for solar field size based on 500,000m^2

Baseline Economic Assumptions

- DOE LCOE Methodology
  - 2002 real dollars
- IPP Project Financing
  - 30 year cash flow model
  - Current financial incentives
  - Sargent & Lundy financial assumptions

SEGS VI Baseline

Site: Kramer Junction	Solar Only	Hybrid (25%)
Plant size, net electric [MWe]	30	30
Collector Aperture Area [km^2]	0.188	0.188
Thermal Storage [hours]	0	0
Solar-to-electric Efficiency. [%]	10.6%	10.7%
Plant Capacity Factor [%]	22.2%	30.4%
Capital Cost [$/kWe]	3008	3204
O&M Cost [$/kWh]	0.046	0.034
Fuel Cost [$/kWh]	0.000	0.013
Levelized Cost of Energy [2002$/kWh]	0.170	0.141

Near-Term Technology

Parabolic Trough Plant

- Current State-of-the-Art (Plant built today)
  - 50 MWe (~100 bar, 700F, 37.5% gross)
  - LS-2+ Collectors (391 C)
  - Receiver – Solel UVAC2
  - Solar only or hybrid
  - Solar multiple 1.5
  - No thermal storage

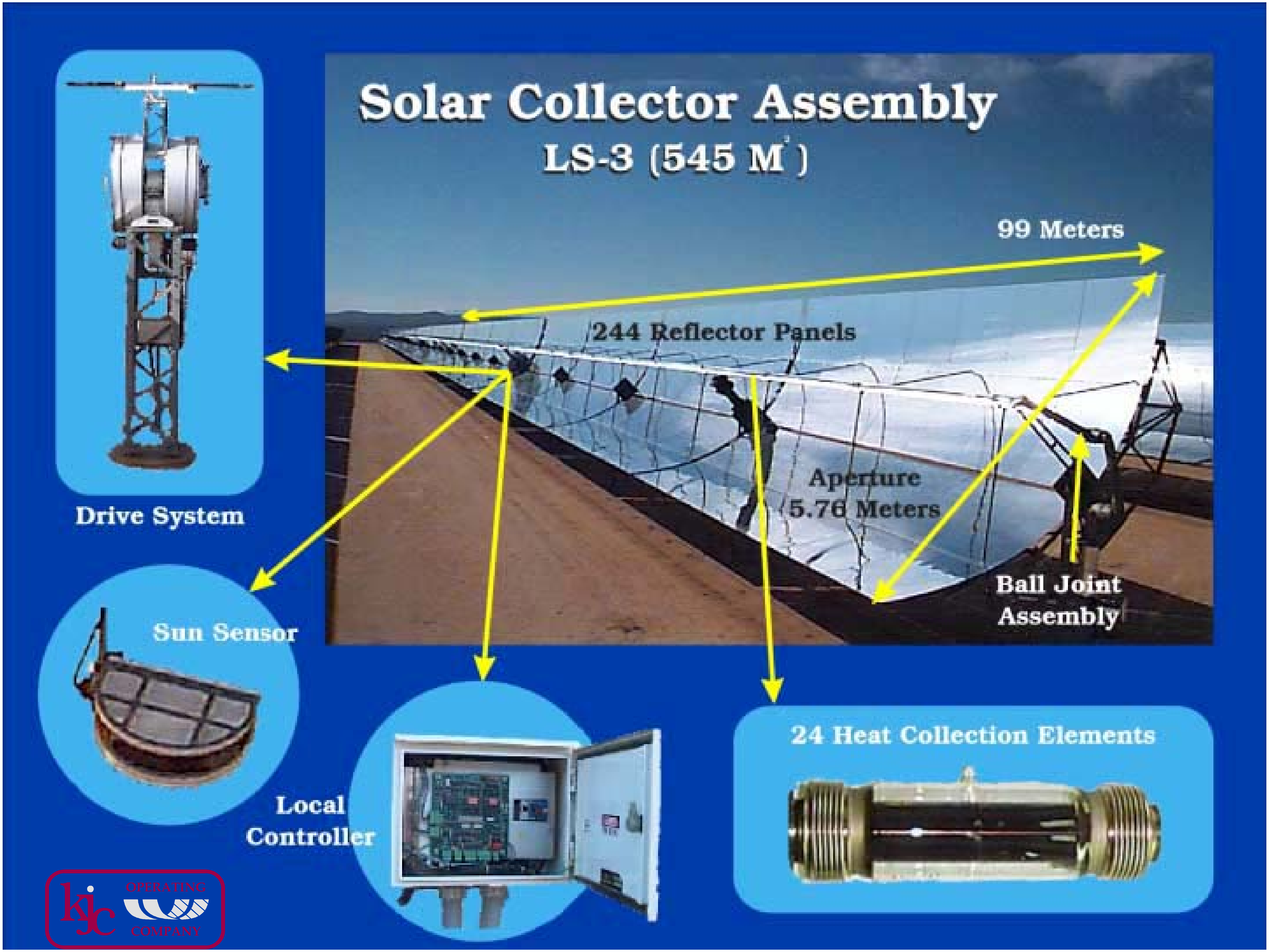
Current State-of-the-Art

50 MWe Trough Plant

Site: Kramer Junction	Solar Only	Hybrid (25%)
Plant size, net electric [MWe]	50	50
Collector Aperture Area [km^2]	0.312	0.312
Thermal Storage [hours]	0	0
Solar-to-electric Efficiency. [%]	13.9%	14.1%
Plant Capacity Factor [%]	29.2%	39.6%
Capital Cost [$/kWe]	2745	2939
O&M Cost [$/kWh]	0.024	0.018
Fuel Cost [$/kWh]	0.000	0.010
Levelized Cost of Energy [2002$/kWh]	0.110	0.096

Opportunities for Reducing the Cost of Energy

- Concentrator Design
- Advanced Receiver Technology
- Thermal Energy Storage
- Plant Size
- O&M
- Design Optimization/Standardization
- Power Park
- Competition
- Financial



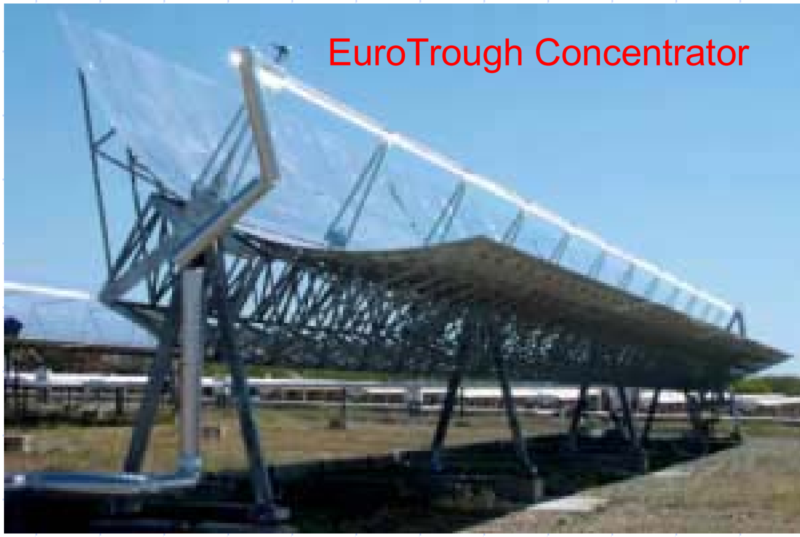
Solar Collector Assembly
LS-3 (545 M²)
99 Meters
244 Reflector Panels
Aperture
5.76 Meters
Ball Joint
Assembly
Drive System
Sun Sensor
Local
Controller
24 Heat Collection Elements
OPERATING
COMPANY

Trough Concentrator
Cost Reduction Opportunities

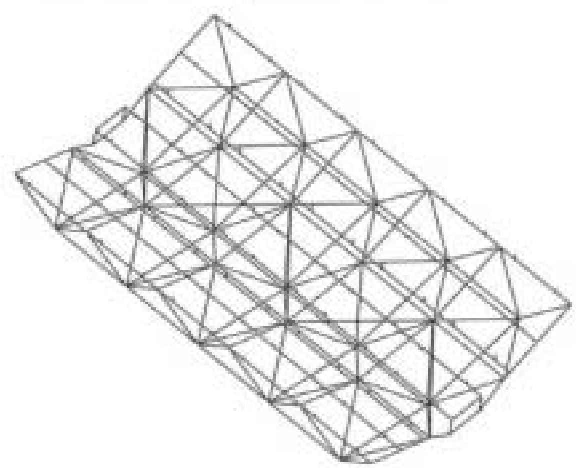
- LS-2 Baseline
- Reduce Costs
  - Increase Size
  - Optimized Structure
  - Competition
- Improved Performance
  - Increase mirror reflectivity
  - Increase cleanliness

Trough Concentrator

Current Development



Duke Solar Concentrator



Concentrator Size

Impact on Cost of Energy

Site: Kramer Junction	**LS-2 50**	**LS-3 100**	**LS-3 150**
Aperture (m)	5	5.75	5.75
Length (m)	50	100	150
Aperture Area (m^2)	235	545	818
Number of collectors relative to LS-2 size collector	100%	43%	29%
Number of receivers relative to LS-2 size collector	100%	87%	87%
Est. Collector Cost ($\$/m^2$)	233	208	202
Levelized Cost of Energy 2002$/kWh	0.110	0.103	0.102

Trough Receiver
Cost Reduction Opportunities

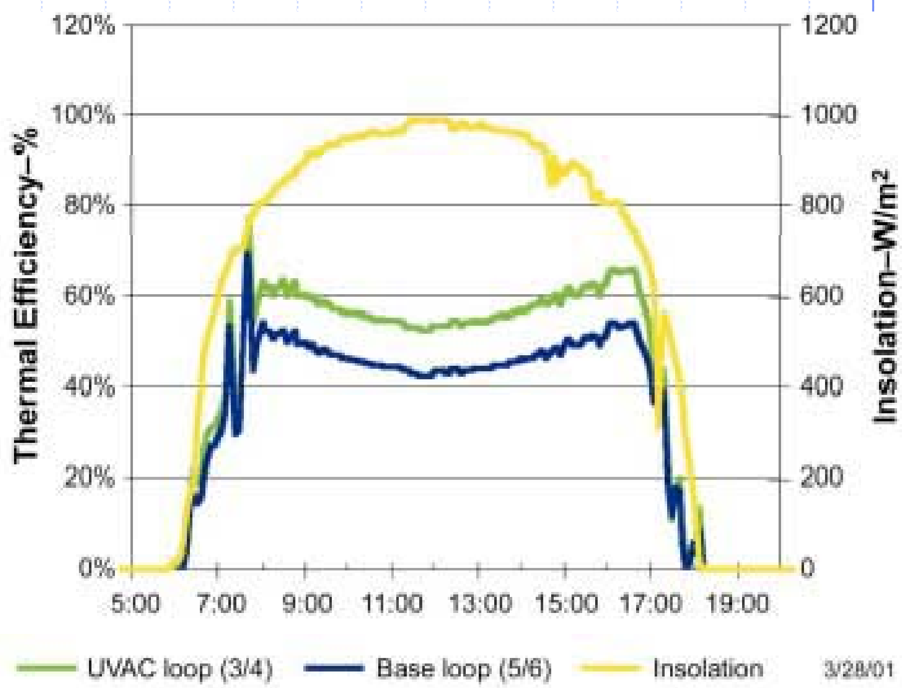
- Improved Reliability
  - Reduced Breakage (G/M Seal)
  - Durability in Air at Temperature
- Improved Performance
  - Thermo/Optic Properties
  - Higher Temperatures
- Reduced Cost
  - Selective Coating Process
  - Design Changes
  - Competition

Solel UVAC Receiver
Test Results

UVAC Selective Coating Property Test Results

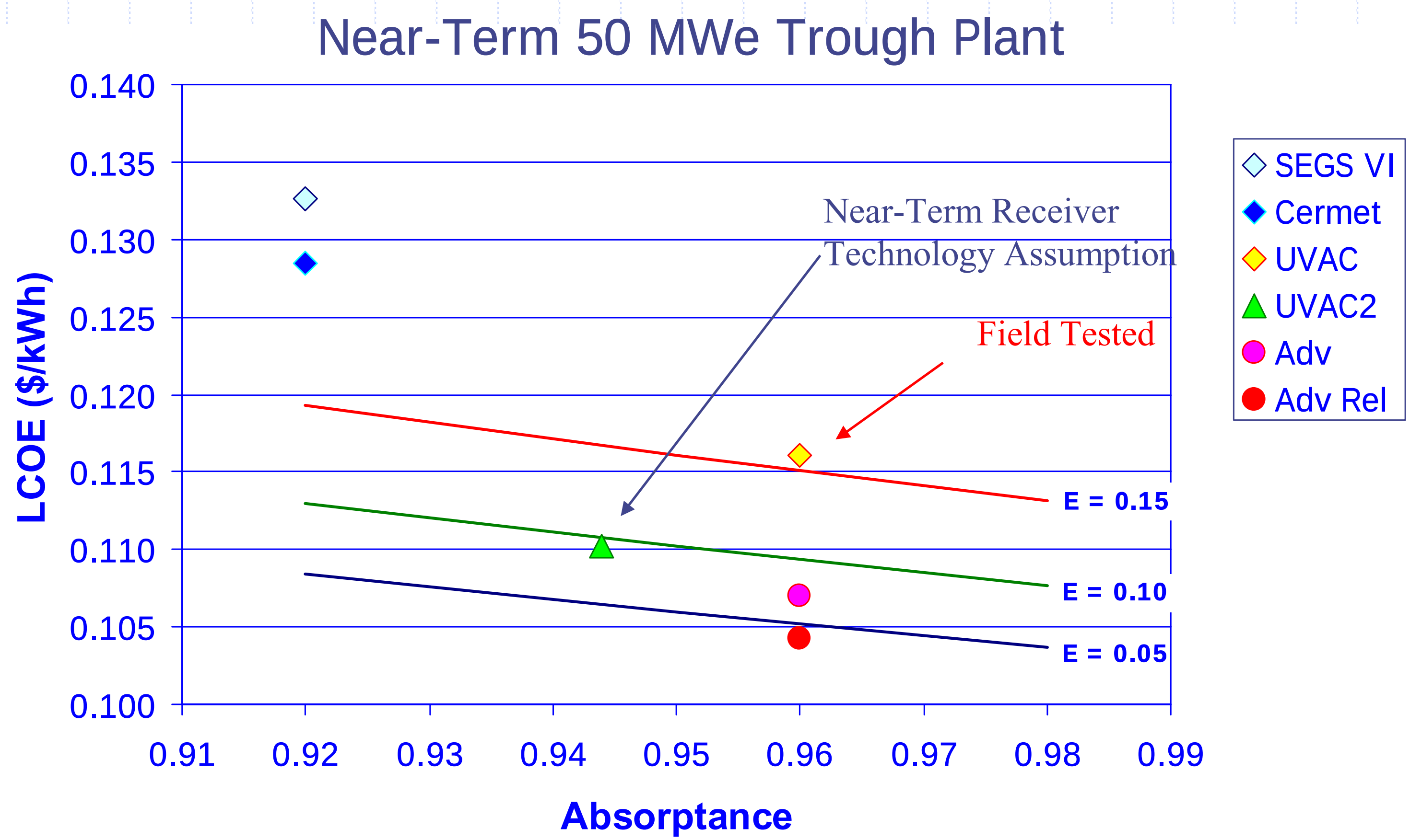
Receiver	Luz Cermet	Solel UVAC	
Data source	SNL test	SNL test	SPF test for Solel
Envelope solar transmittance	0.930	0.965	NA
Coating solar absorptance	0.915	0.95-0.96	>0.944
Coating thermal emittance	0.14 @ 350°C	0.135 @ 400°C	0.091 @ 400°C

UVAC Field Test Results



Trough Receiver Technology

Impact on the Cost of Energy



Thermal Storage

Developments

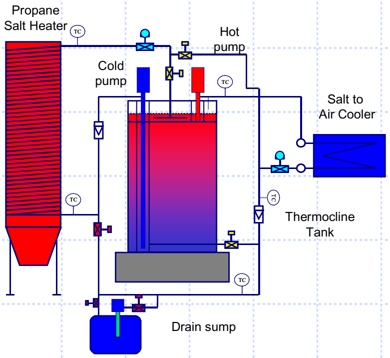
Near-term Option

- **Two Tank Molten Salt Storage**
  - **Leveraged experience from Solar Two's TES.**
  - **Heat transferred via an oil-to-salt HX.**

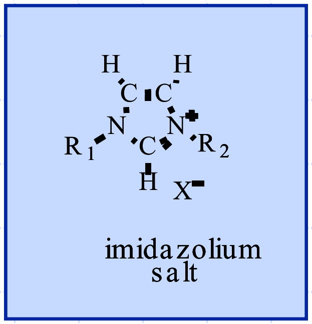
Advanced Technologies

- **Thermocline Molten Salt System**
  - **Single tank. Hot and cold separated with thermal gradient.**
  - **Low-cost filler material**
  - **Design and operation more compex than 2-tank**
- **Molten Salt HTF/Storage**
  - **Increased operating temperature (450-500C), reduced piping cost, reduced parasitics**
  - **Freeze protection of fluid (120C), SCA interconnection, increased O&M complexity**
- **Advanced HTF**
  - **Imidazolium salts have potential to be thermally stable to above 400 C with very low freezing point**
  - **Compatible with alloys used in solar plants, non-flamable, low vapor pressure**
  - **Cost and temperature stability issues**

Solar Two Molten Salt Thermal Storage



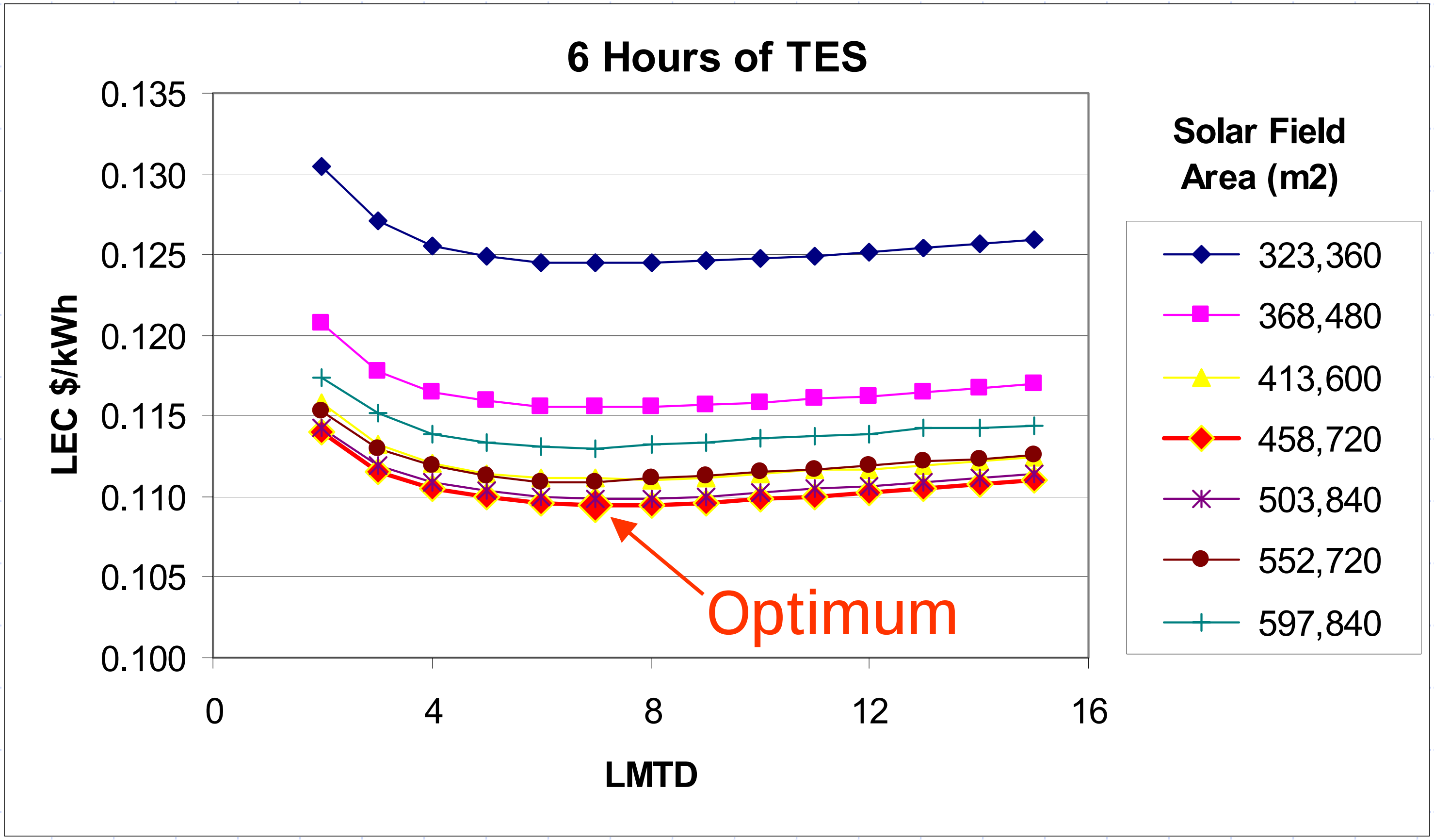
Prototype Thermocline Storage



Thermal Storage Design Optimization

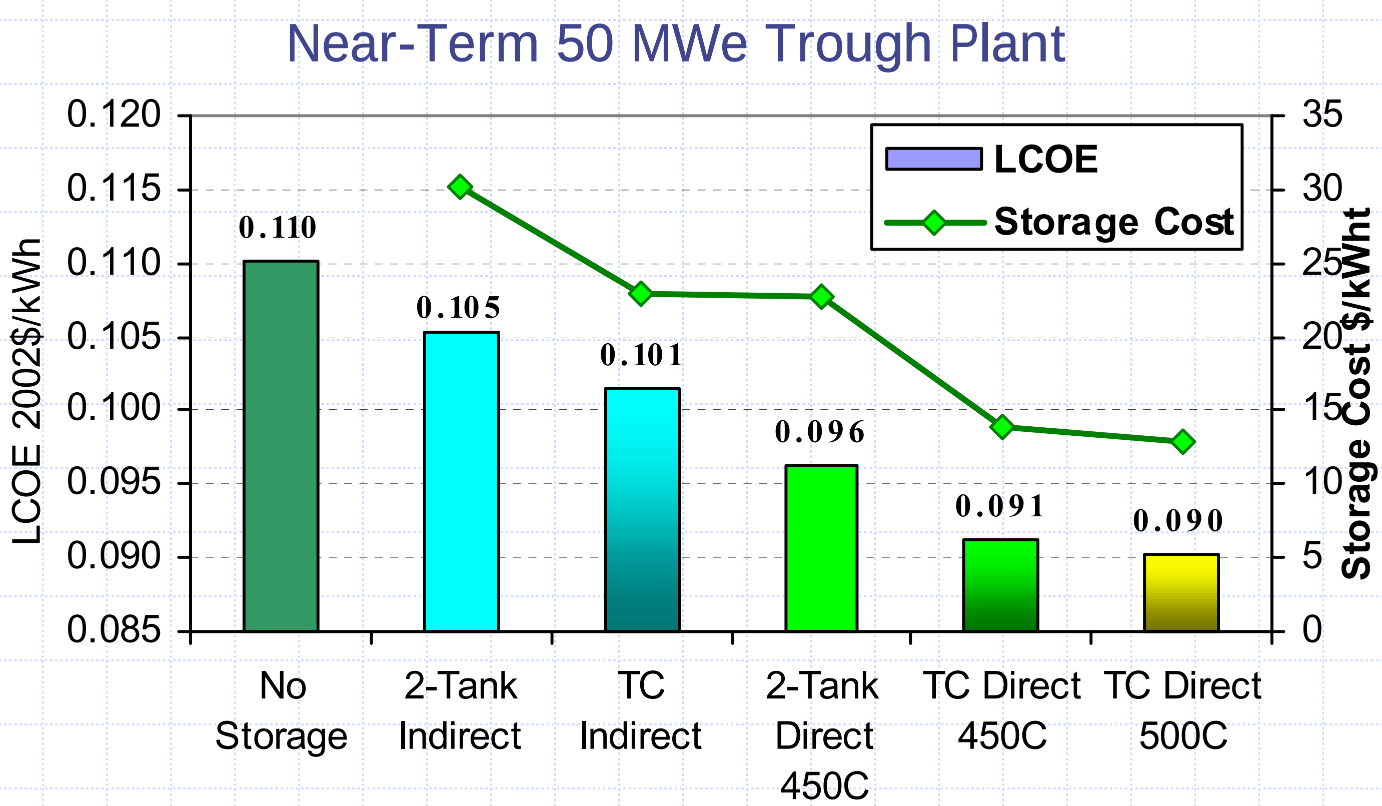
Impact on Cost of Energy

Near-Term 50 MWe Trough Plant



Thermal Storage Technology

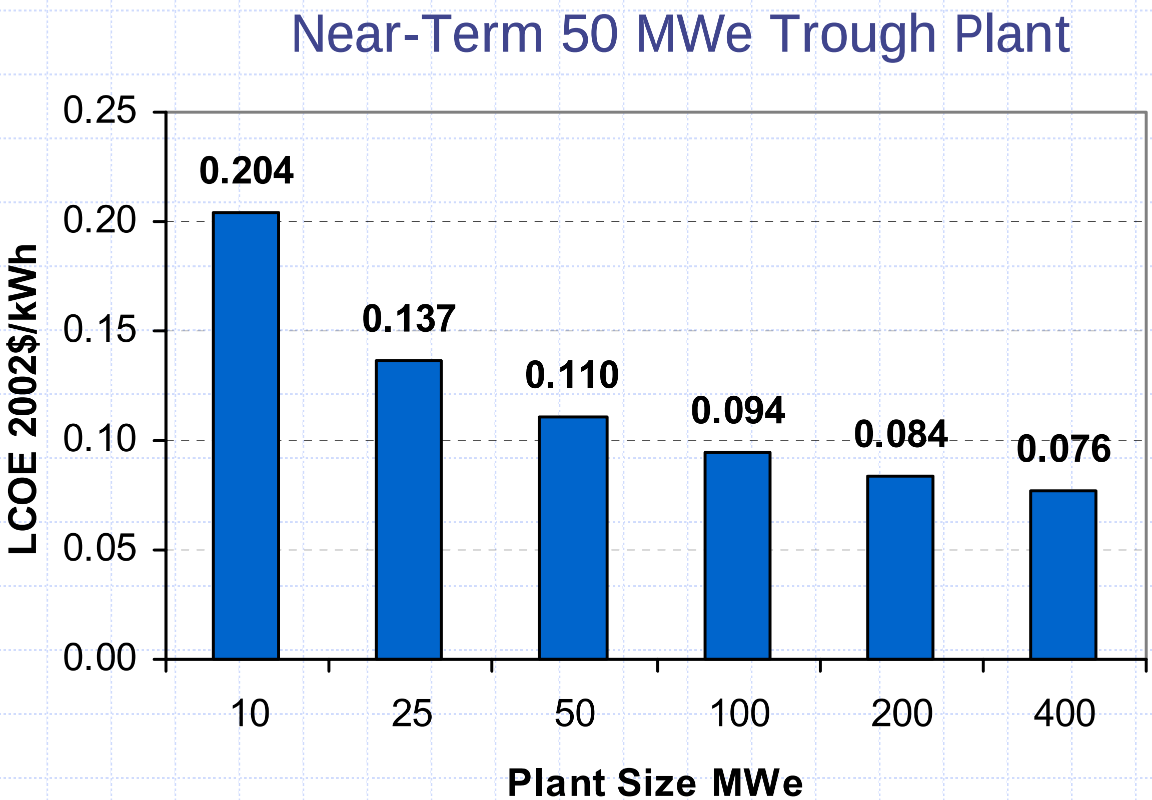
Impact on Cost of Energy



Enabling Technologies
- Salt HTF
- Thermocline Storage

Plant Size

Impact on Cost of Energy



Enabling Technologies
- Ball Joints
- Salt HTF

Solar Resource

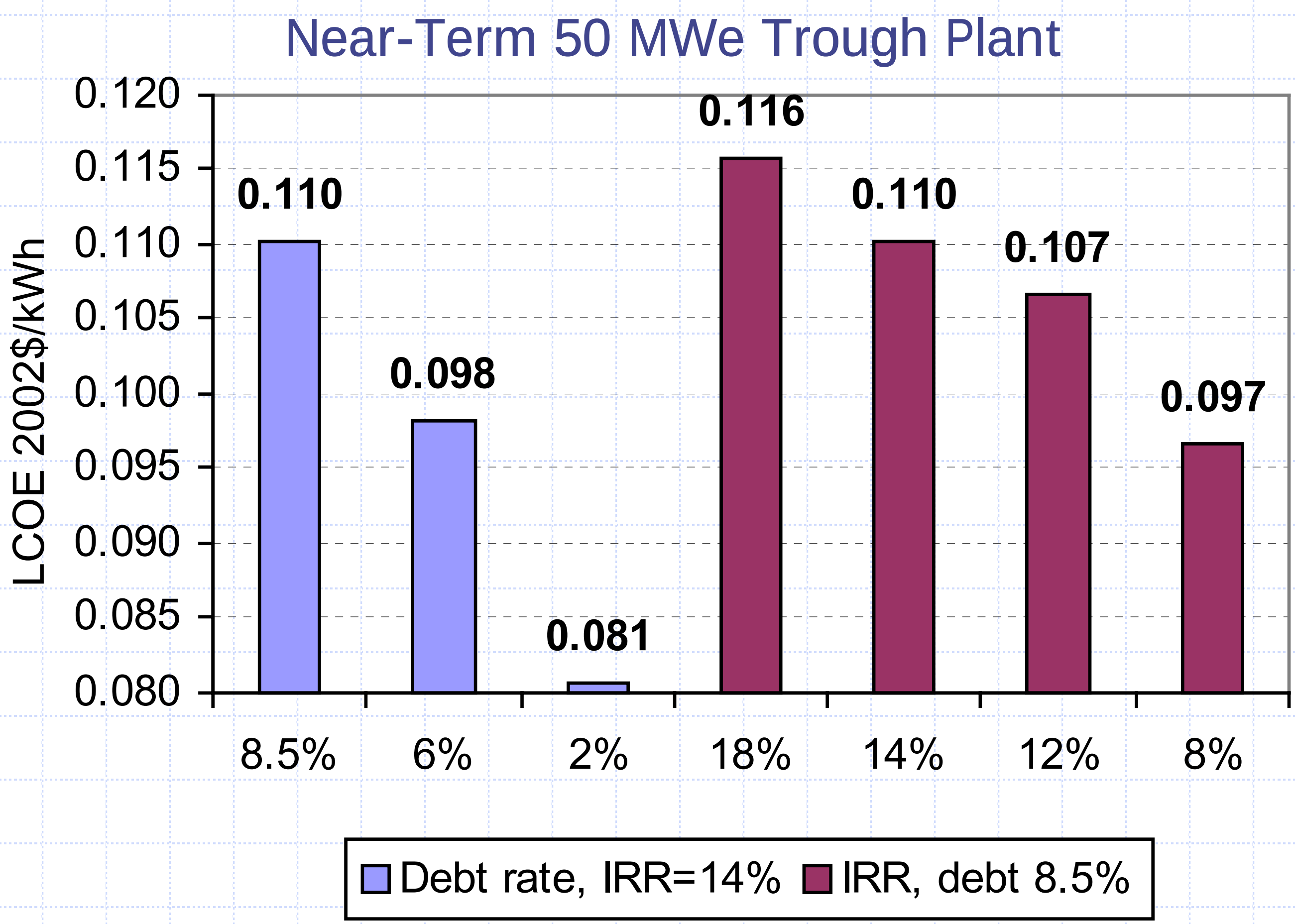
Impact on Cost of Energy

Site	DNI Resource kWh/m^2day	LCOE $/kWh	Source
Kramer Junction, CA	8.0	0.110	a
Daggett, CA	7.6	0.115	b
Las Vegas, NV	7.1	0.125	b
Phoenix, AZ	6.9	0.124	b
El Paso, TX	6.8	0.127	b
Cedar City, UT	6.4	0.147	b
Reno, NV	6.4	0.147	b

Source: a – KJC Operating Company, 1999 DNI data
b – NREL TMY 2 Data, http://rredc.nrel.gov/

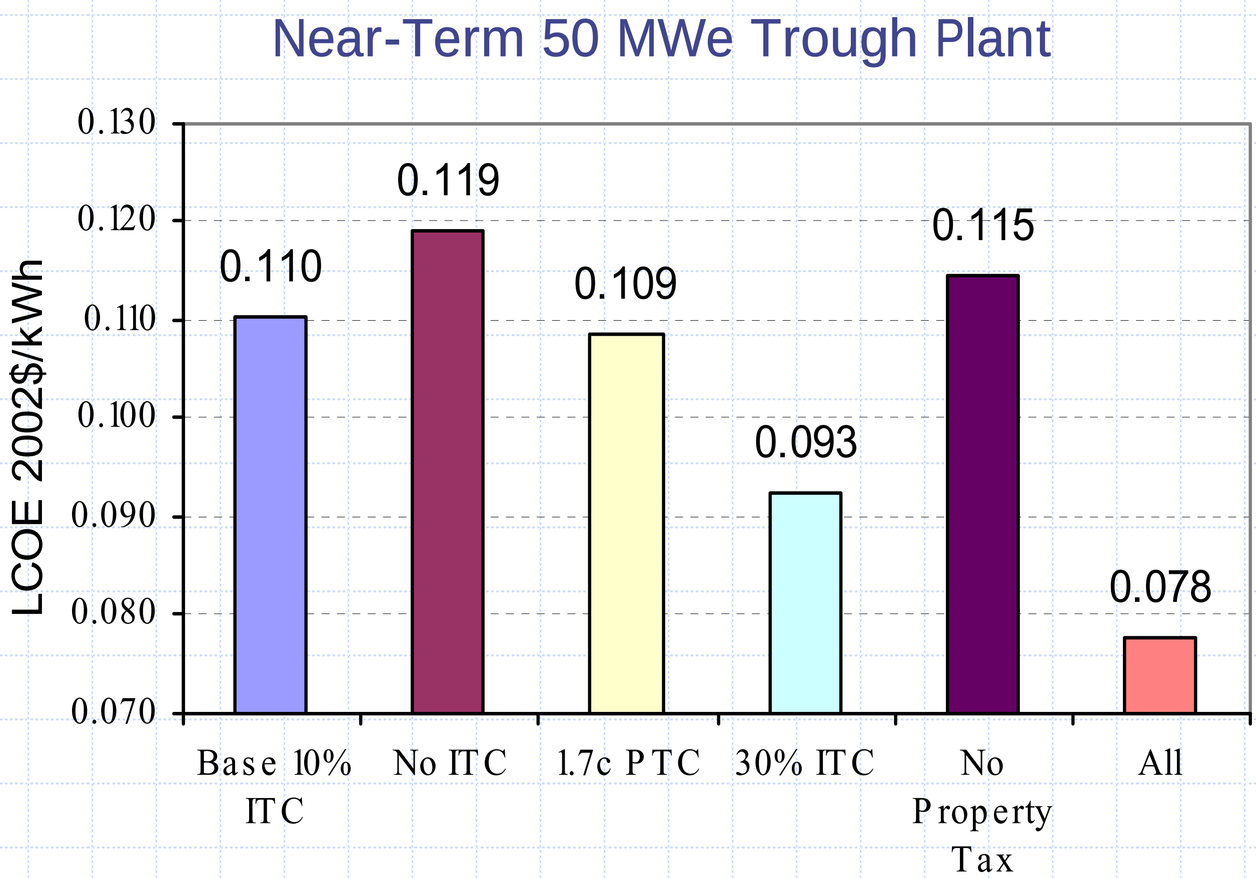
Cost of Capital

Impact on Cost of Energy



Tax Incentives

Impact on Cost of Energy

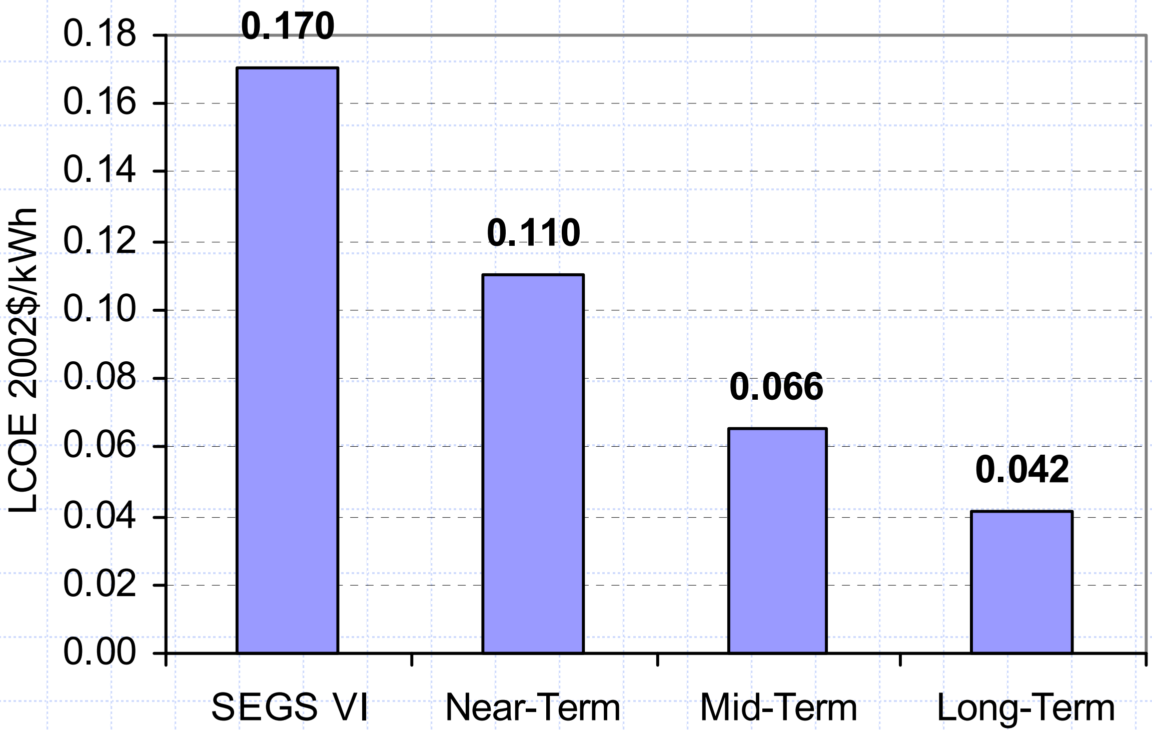


Trough Development Scenario

	SEGS VI 1989	Near-Term	Mid-Term	Long-Term
Plant Size: MWe Solar Multiple	30 1.2	50 1.5	100 2.5	400 2.5
Collector Receiver	LS-2 Luz	LS-2 UVAC2	LS-3+ Adv	Adv Adv
HTF	VP-1 390 C	VP-1 390 C	Salt 450 C	Salt 500 C
TES	NA	NA	12 hrs TC Dir	12 hrs TC Dir
Capacity Factor	22%	30%	56%	56%
Solar to Electric η	10.6%	13.4%	16.2%	17.2%
Cost Reduction			5%	20%
Capital Cost $/kWe	2954	2865	3416	2225
O&M Cost $/kWh	0.0462	0.0233	0.0103	0.0057

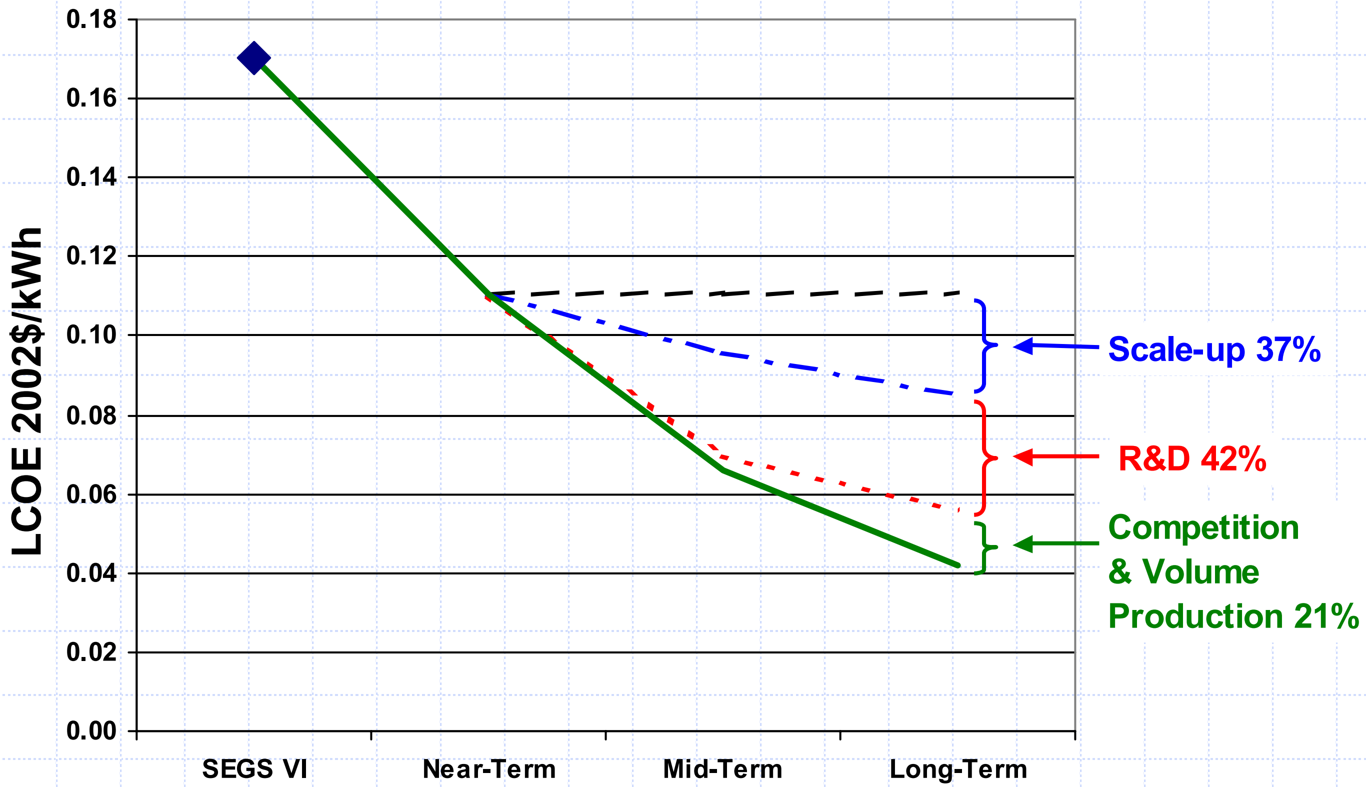
Trough Development Scenario

Cost of Energy



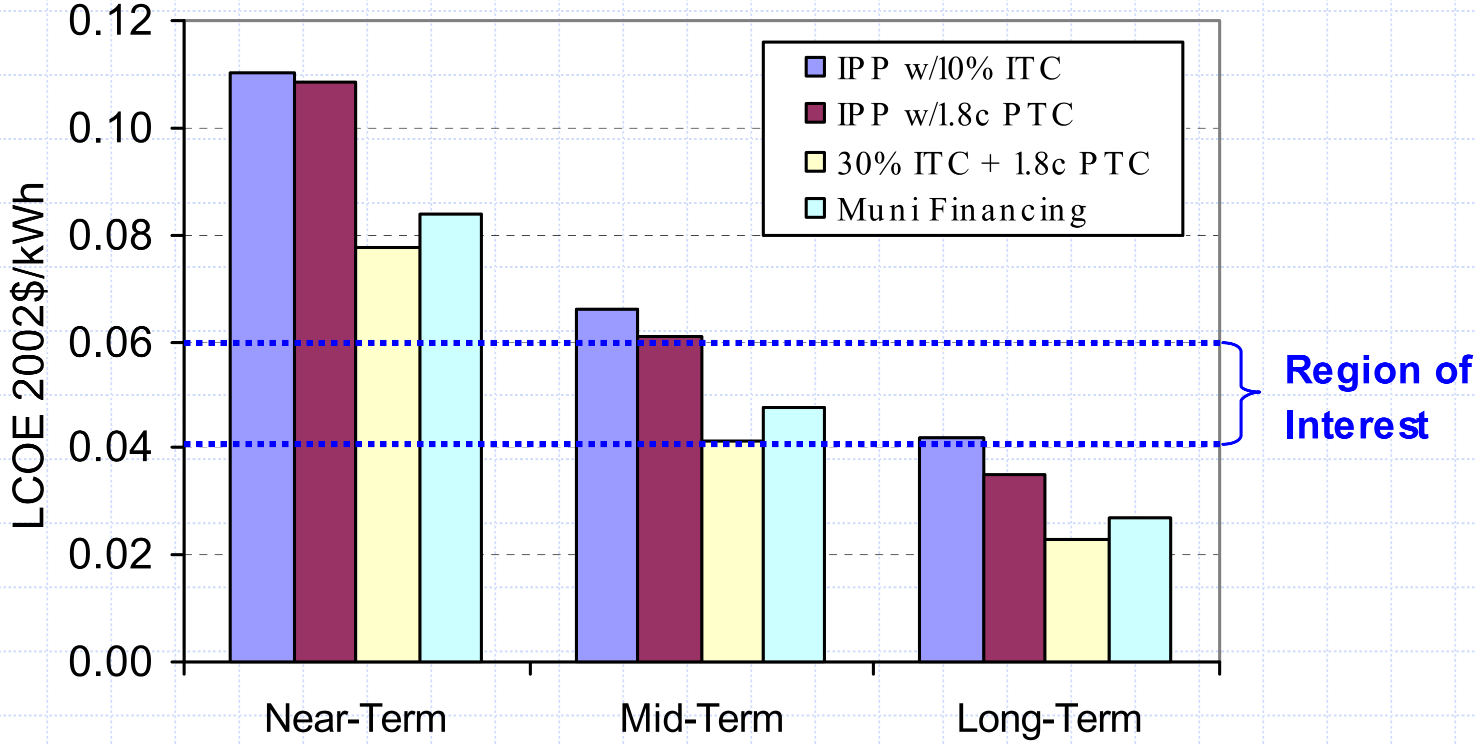
Trough Development Scenario

Breakdown of Cost Reduction



Trough Power Plant Scenarios

with Different Financing Assumptions



Conclusions

CSP Systems Analysis & Implications

- Market assessment important
  - Identification of market and key requirements
  - Identification of appropriate metrics
- Integrated analysis tools are essential
  - Helps in defining metrics
  - Technology assessment
  - Decision Making